Thermal behavior as indicator of hyperons in binary neutron star mergers

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Encuentros de Física Nuclear FNUC en los
XV CPAN Days,
Santander

2-6 October 2023

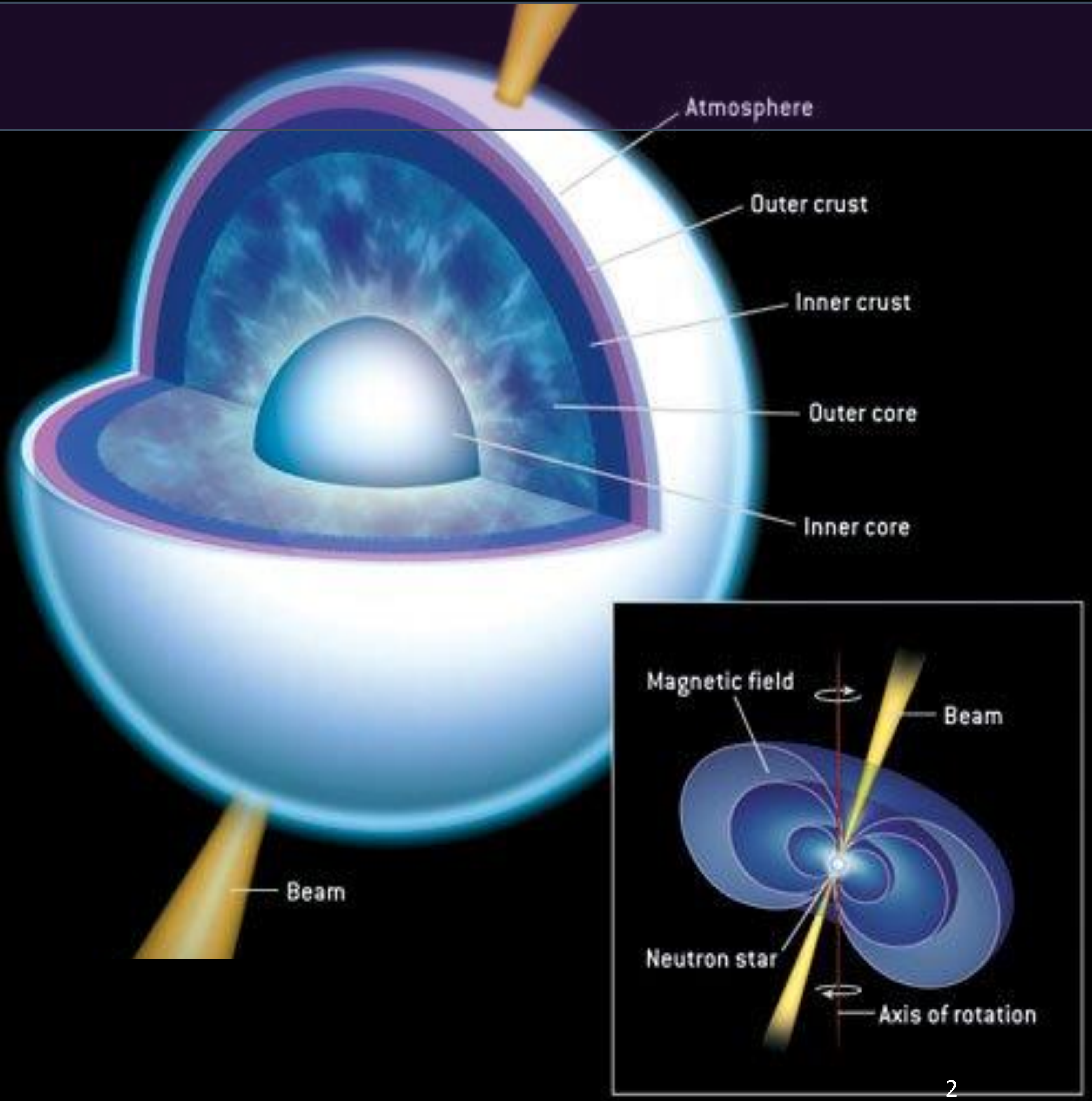
Neutron stars properties

- They are formed by the gravitational collapse of the remnant of a massive star after a supernova explosion.

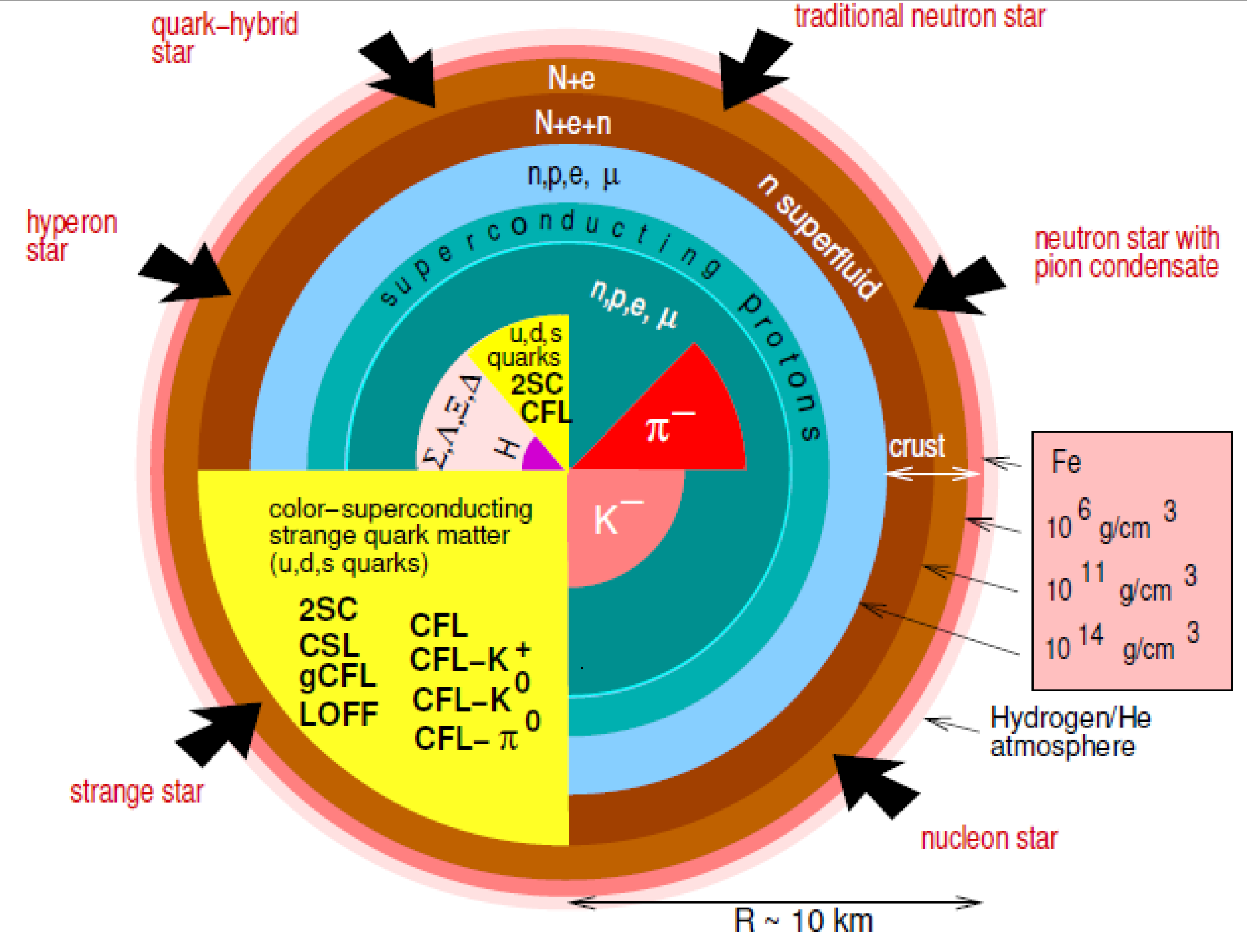
- Exotic properties:

- $M \cong (1-2)M_{\odot}$
- $R \cong (10-15)$ km
- $\rho_C \approx 10^{18}$ kg/m^3 (≈ 1 fm^{-3})

- The outer parts (atmosphere and crust) are made of nuclei, neutron gas and electrons.



The core of a neutron star



F. Weber, Prog.Part.Nucl.Phys.54:193-288,2005

Outer core

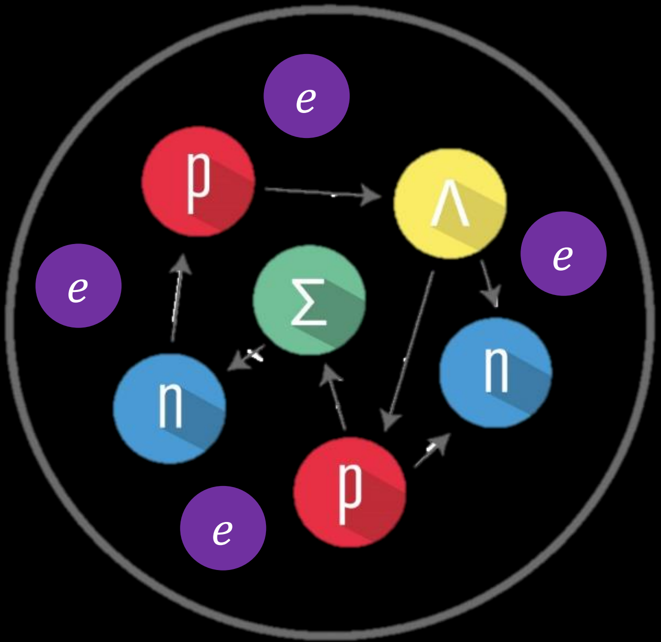
- Nuclear matter
- Leptons

Inner core

- Nuclear matter
- Leptons
- ??? Pion condensate ???
- ??? Kaon condensate ???
- **??? Hyperons ???**
- ??? Deconfined quark matter???

Equation of state of homogenous matter

- We consider homogenous matter made of nucleons, hyperons, electrons and muons.
- Baryons form strongly correlated system.
- Leptons can be treated as non-interacting particles.

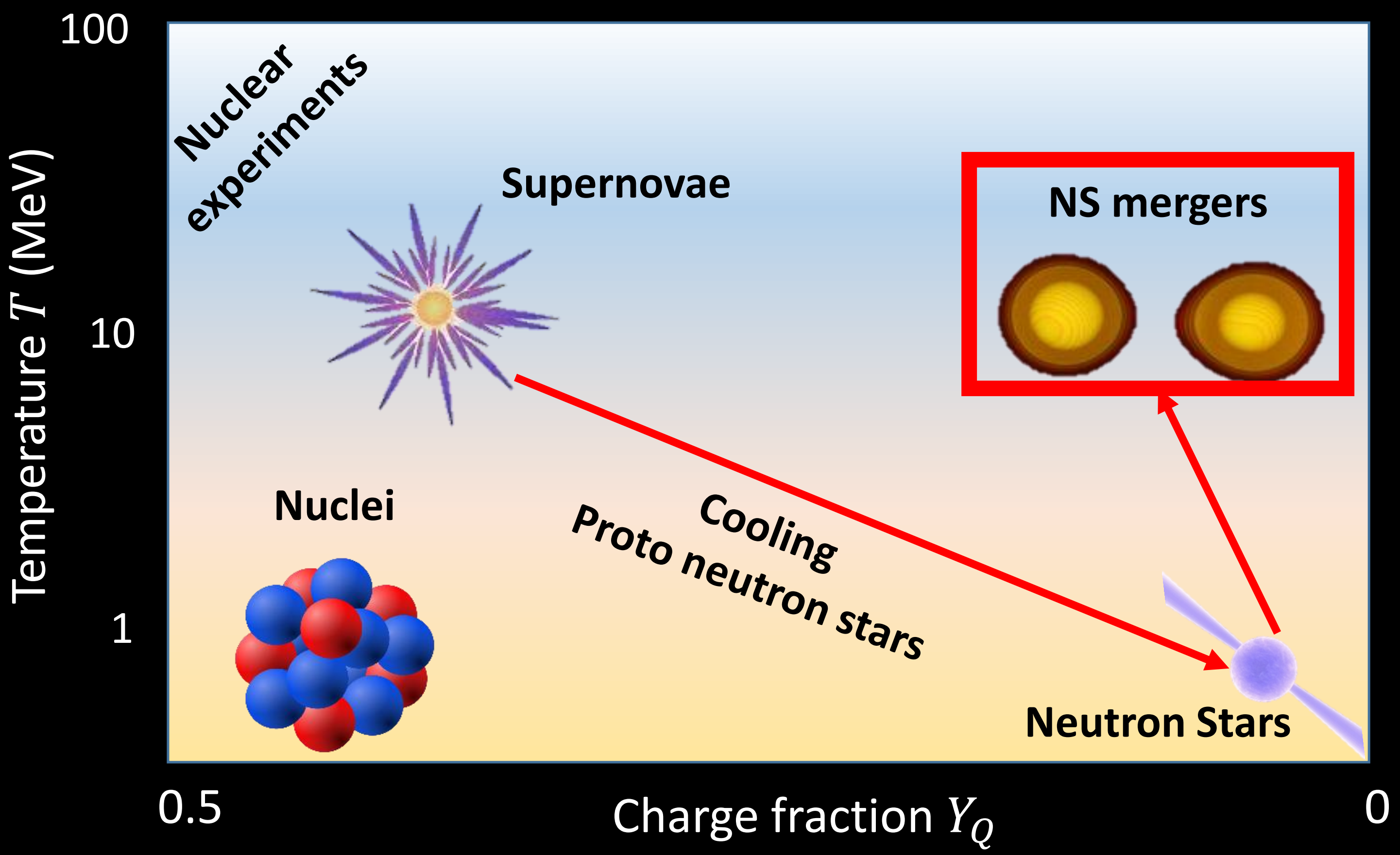


MAIN GOAL – TO OBTAIN THE EQUATION OF STATE FOR ABITRARY CONDITIONS

$$P = P(\rho_B, T, Y_Q)$$

- Microscopic models
  - Brueckner – Hartree Fock
  - Variational approach
- Phenomenological models
  - Relativistic Mean-Field
  - Skyrme Potentials

Equation of State of dense matter and relativistic simulations



- The **Equation of State** (EoS) represents the main input needed for simulating the violent phenomena such as core-collapse supernovae or binary stars mergers.

- The EoS is needed for a wide range of the parameter values:

- Density ρ_B **(0-1.2 fm^{-3})**
- Temperature T **(0-100 MeV)**
- Charge fraction Y_Q **(0 – 0.6)**

Hyperons thermal signatures on the EoS

- Different thermal behavior between the hyperonic EoSs and the nucleonic EoSs

- We define a quantity that is known as thermal index:

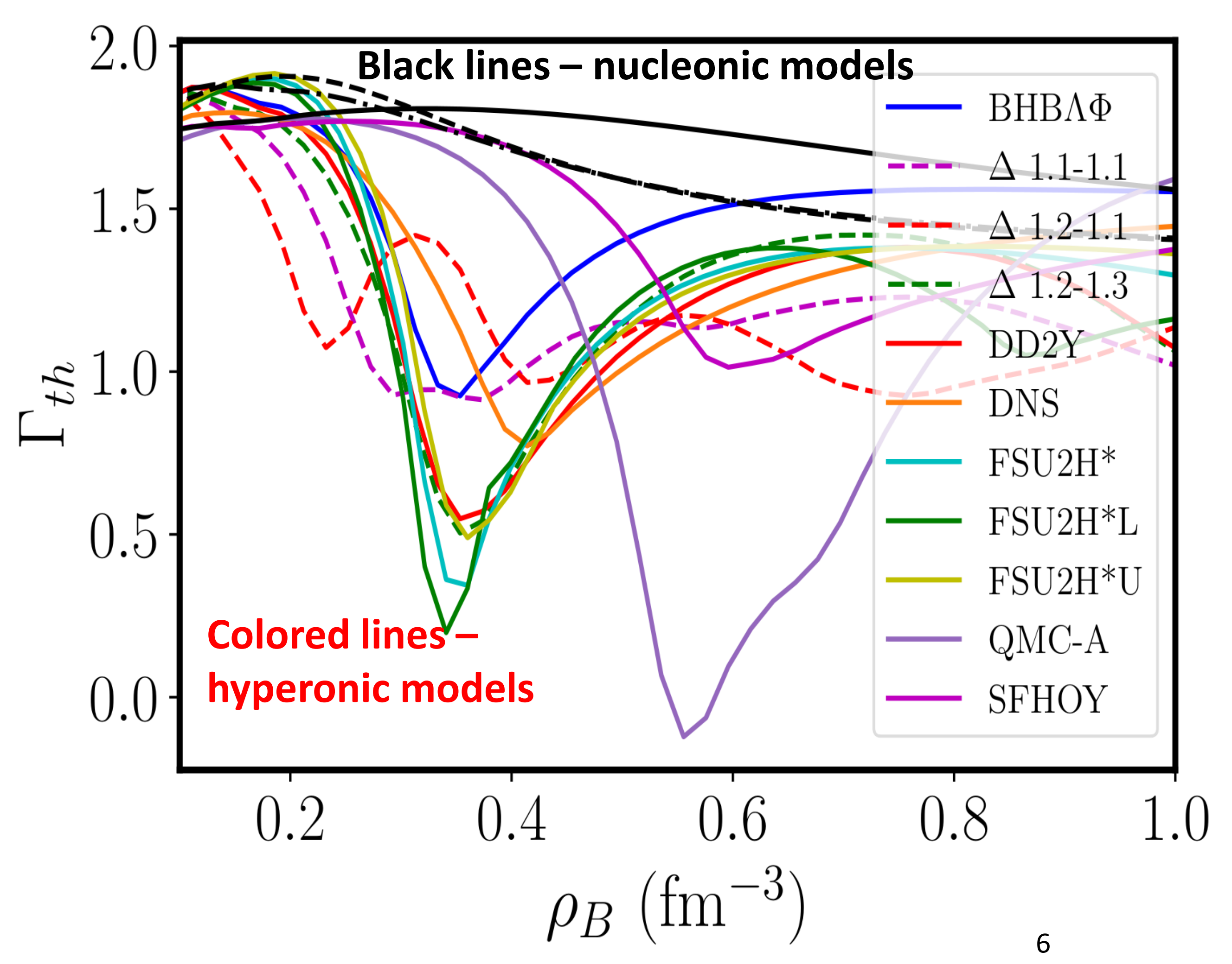
$$\Gamma_{th}(T,\rho_B,Y_Q) = 1 + \frac{P(T,\rho_B,Y_Q) - P(0,\rho_B,Y_Q)}{\epsilon(T,\rho_B,Y_Q) - \epsilon(0,\rho_B,Y_Q)}$$

- The introduction of the hyperons induces a drop in the thermal index

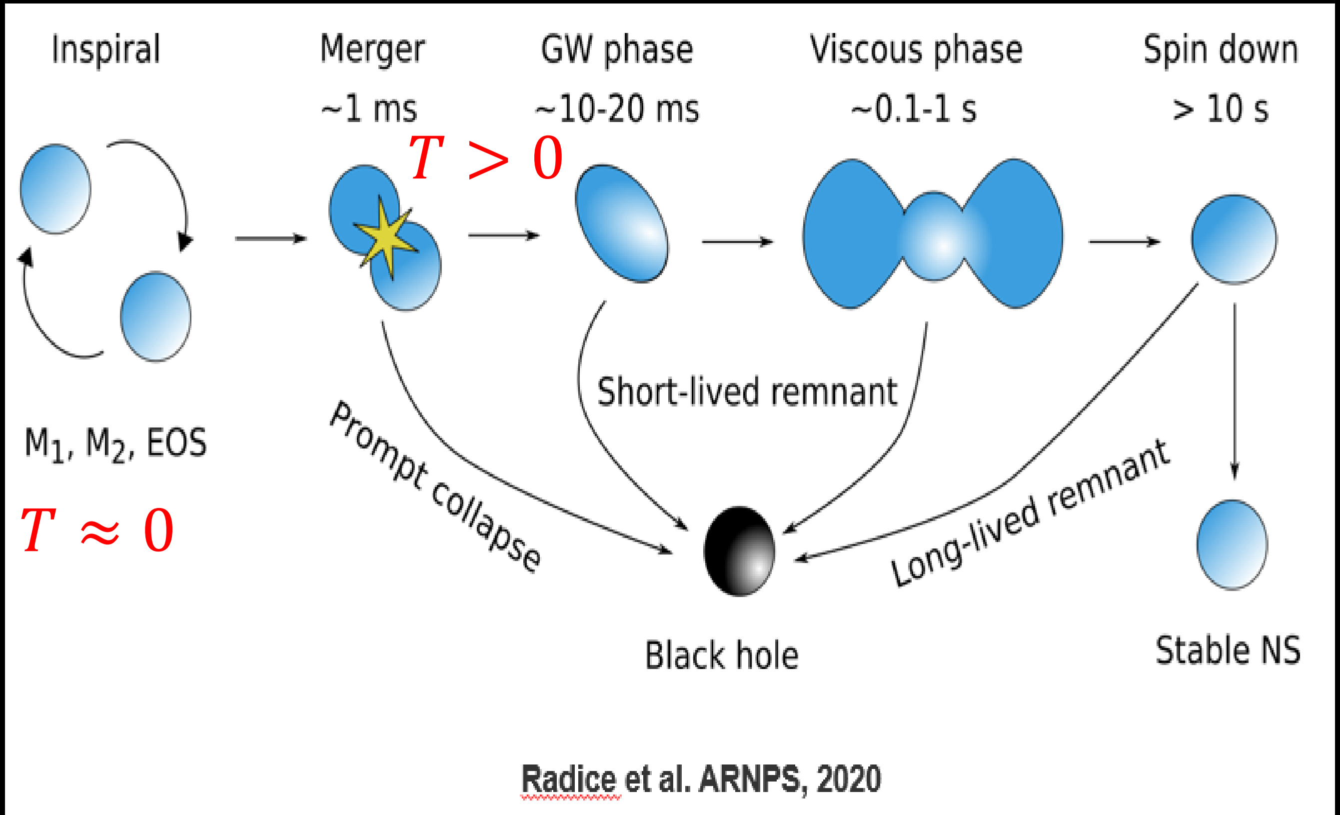
MODEL INDEPENDENT FEATURE

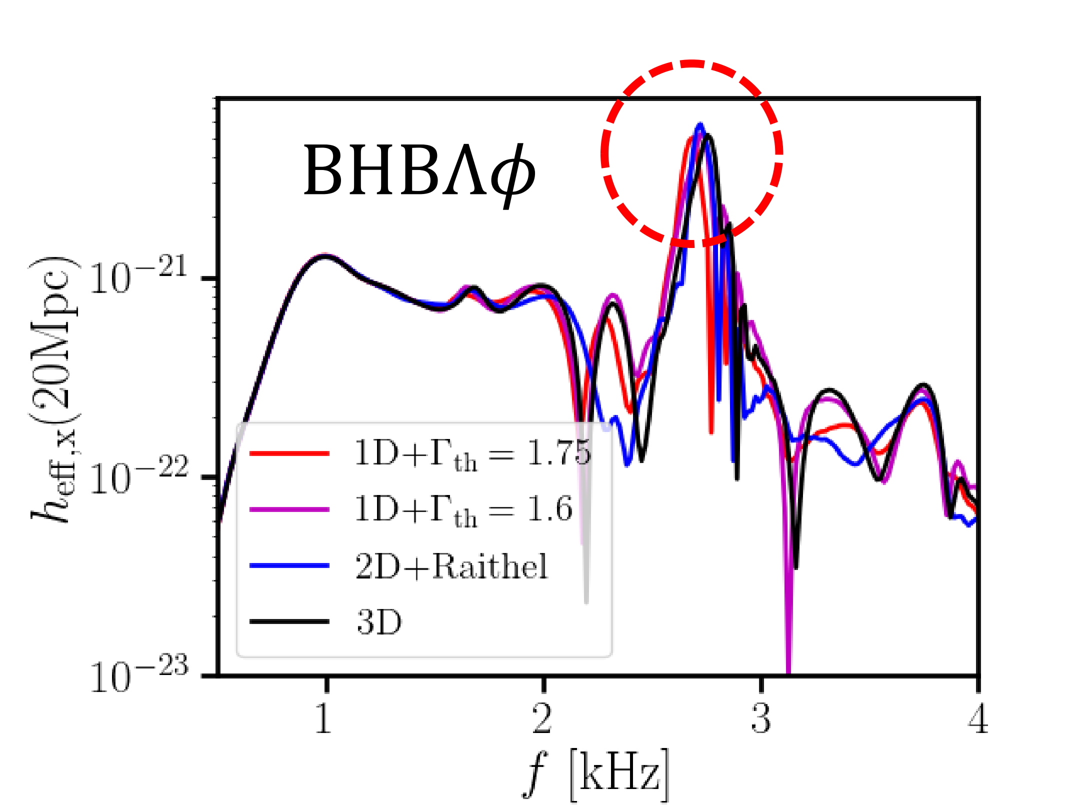
Homogenous matter at

Charge fraction $Y_Q = 0.1$ and Temperature $T = 25$ MeV



Binary neutron stars merger

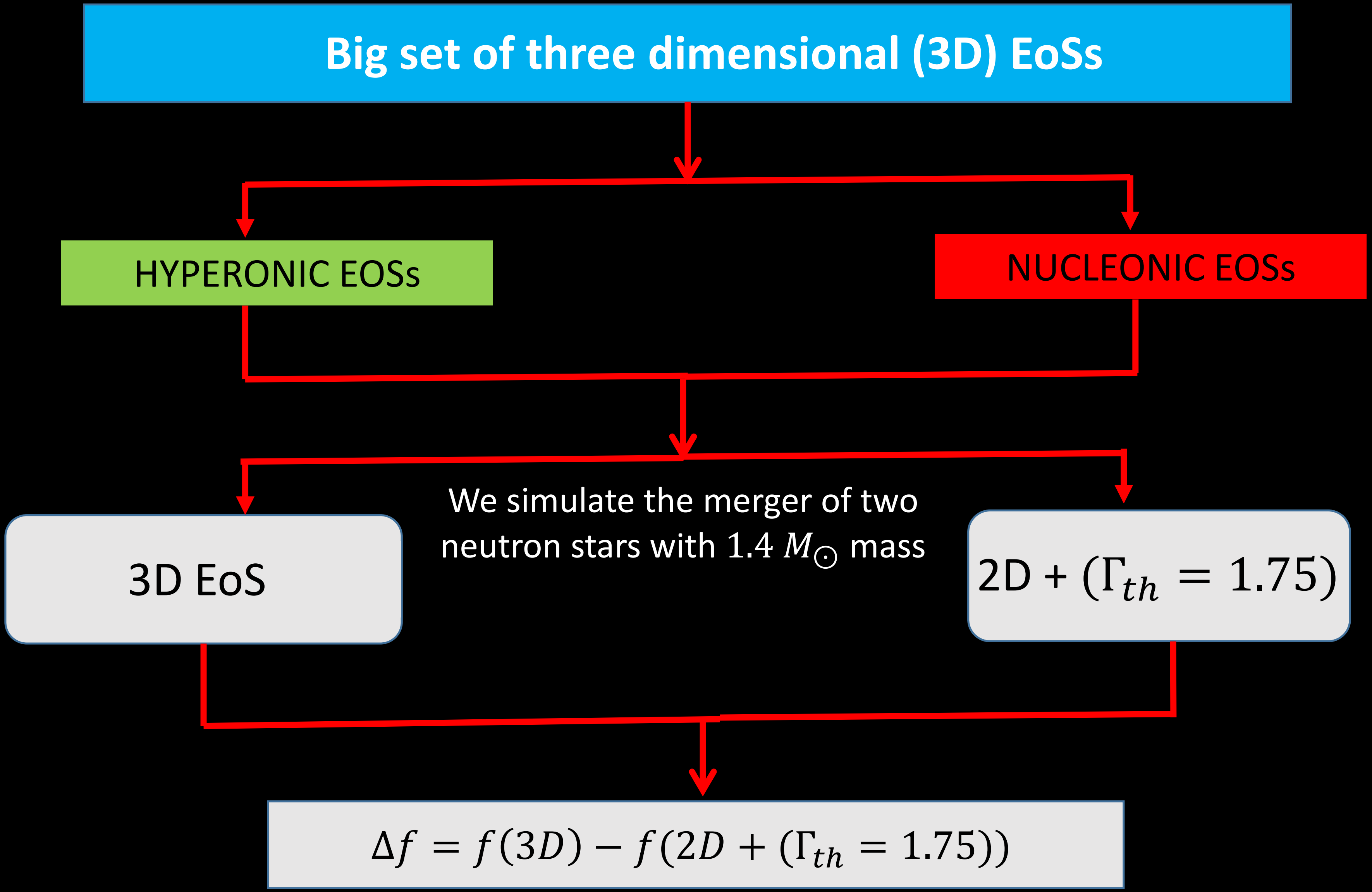




- Thermal effects start to be relevant in the merger phase
- Observable from the GW phase - **postmerger gravitational-wave frequency**

- The new generation of gravitational wave detectors can measure the frequency of the post merger gravitational waves with high precision

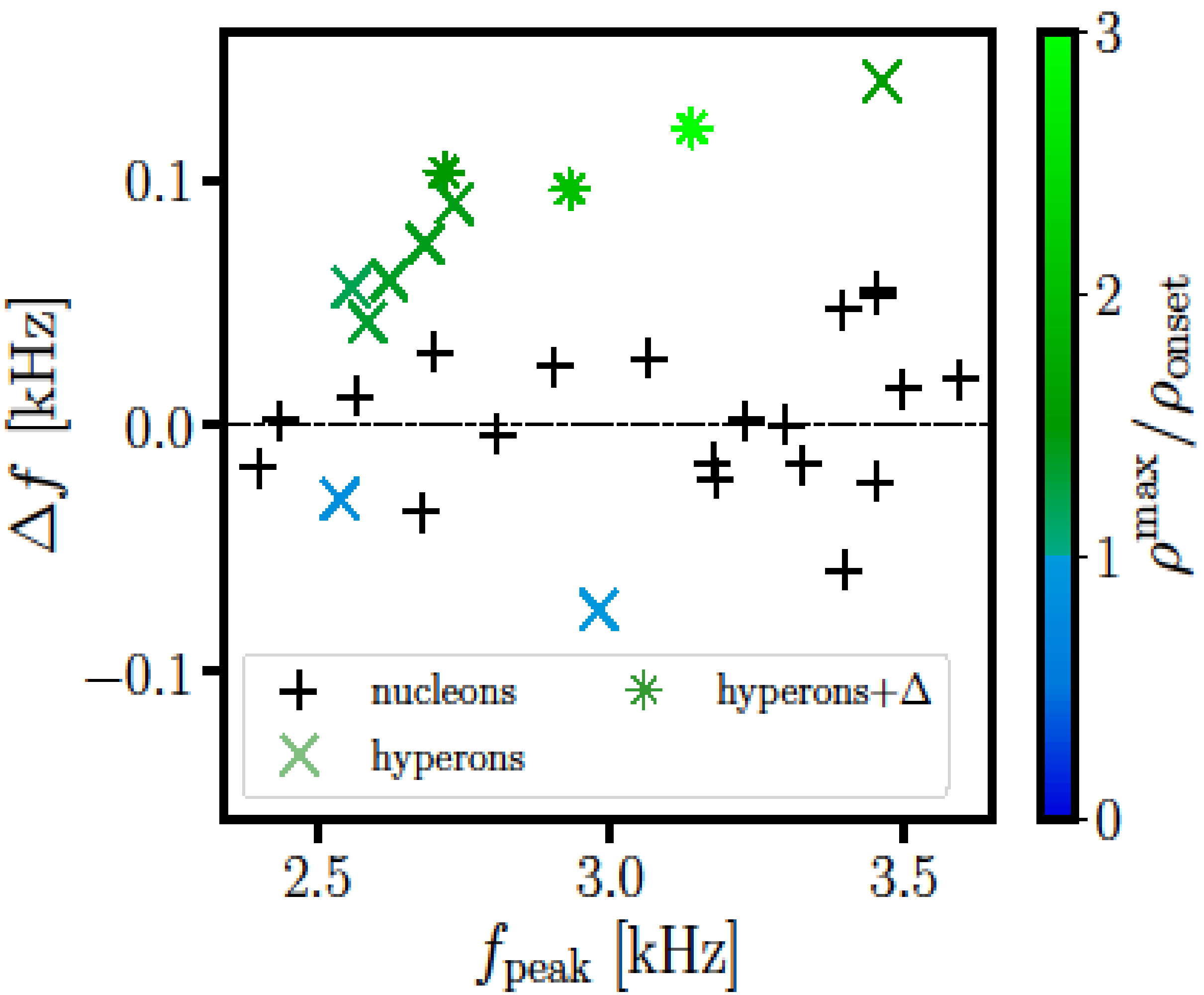
Identifying the hyperonic signature



Signal of hyperons in the GW observables? I

- The difference in the frequencies is defined as:
  $\Delta f = f(3D) - f(2D + \Gamma_{th} = 1.75)$
- All hyperonic models that reach the onset density (density at which the hyperons appear in cold matter) have a positive shift.
- Nucleonic models are grouped around $\Delta f \approx 0$.
- Hyperonic models that do not reach high enough densities are behaving like nucleonic models.

arXiv:2307.03710



Signal of hyperons in the GW observables? II

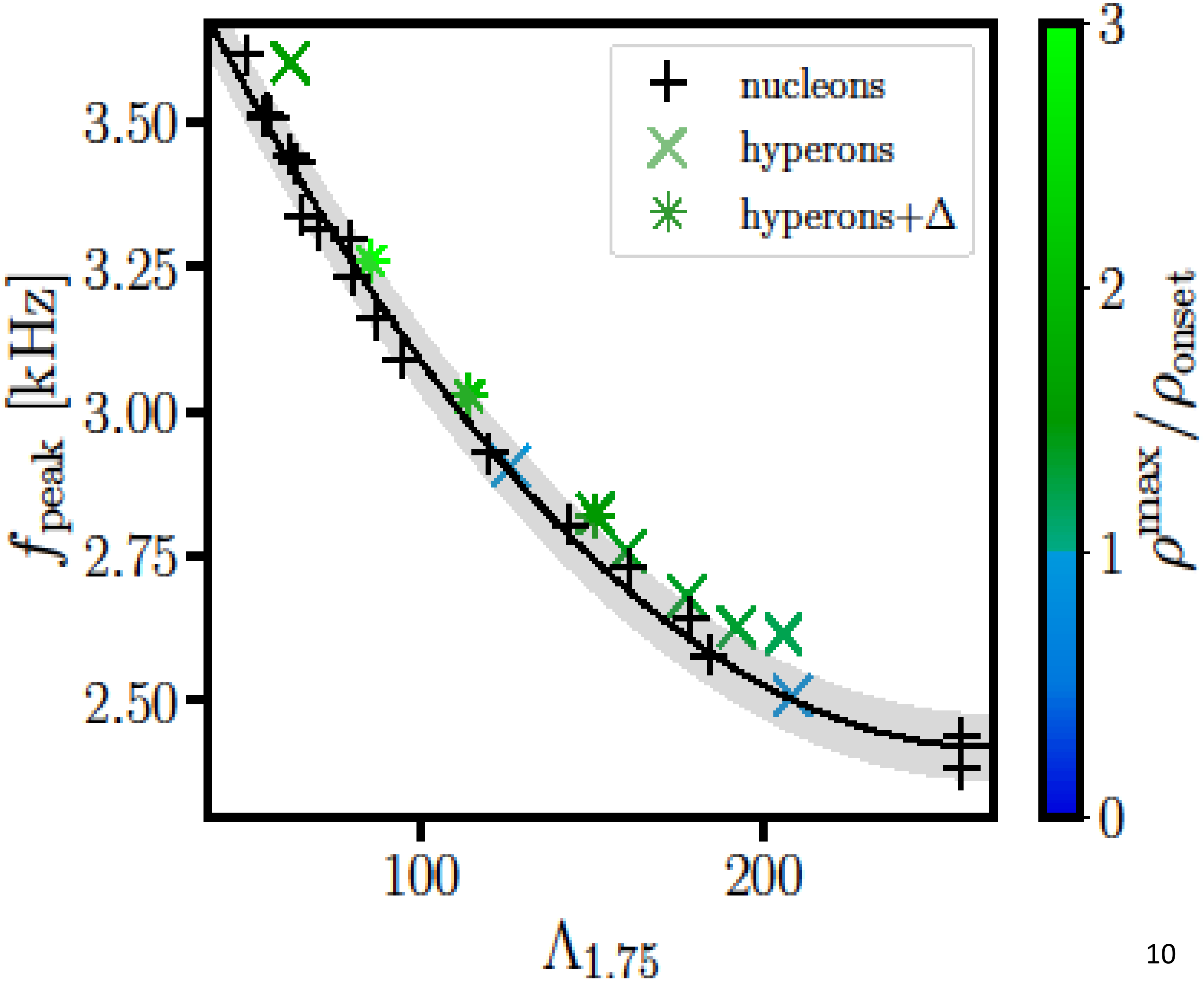
- Another useful way to illustrate the hyperonic imprint is to show the following relation

$$f_{peak} = f_{peak}(\Lambda(1.75M_{\odot}))$$

- All hyperonic models that have densities above the onset ones predict frequency that lies above the second order polynomial fit of the nucleonic models.

- Most of the hyperonic models also lie above the maximum deviation of the nucleonic models.

[arXiv:2307.03710](https://arxiv.org/abs/2307.03710)



Summary

- Neutron stars are natural laboratories for studying matter at extreme conditions.
- In their deepest layers, exotic components, such as hyperons can appear.
- The appearance of the hyperons has a strong impact on both **cold** and **finite-temperature** EoSs.
- We did the first systematic study of the effect of the hyperons in binary neutron star mergers.
- We directly link the thermal behavior of the hyperonic EoSs with a characteristic shift in the dominant gravitational wave frequency.

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Thank you for the attention

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Backup slides

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Winter Meeting 2023
Barcelona

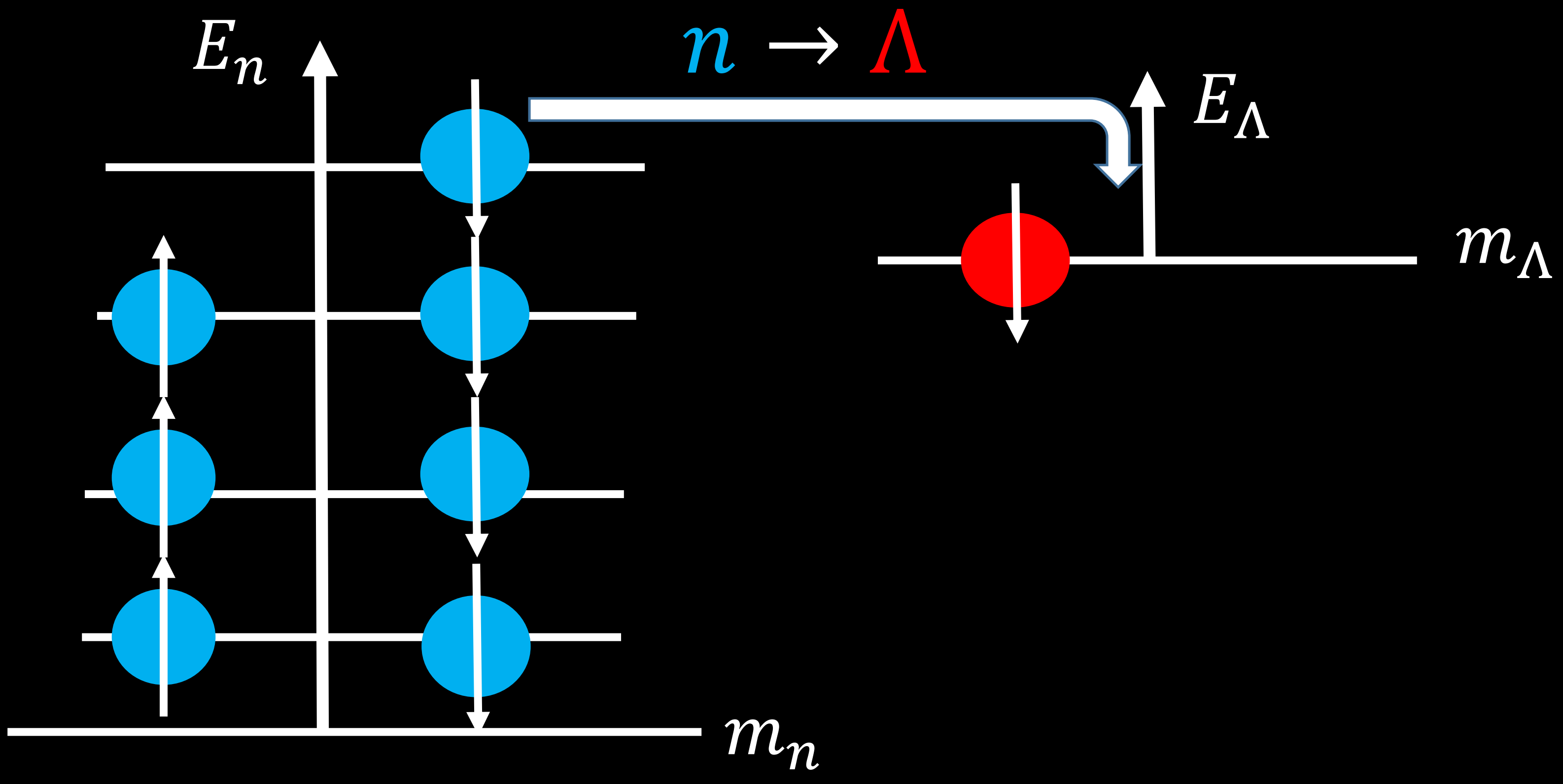
6-7 February 2023

Hyperons in the neutron stars?

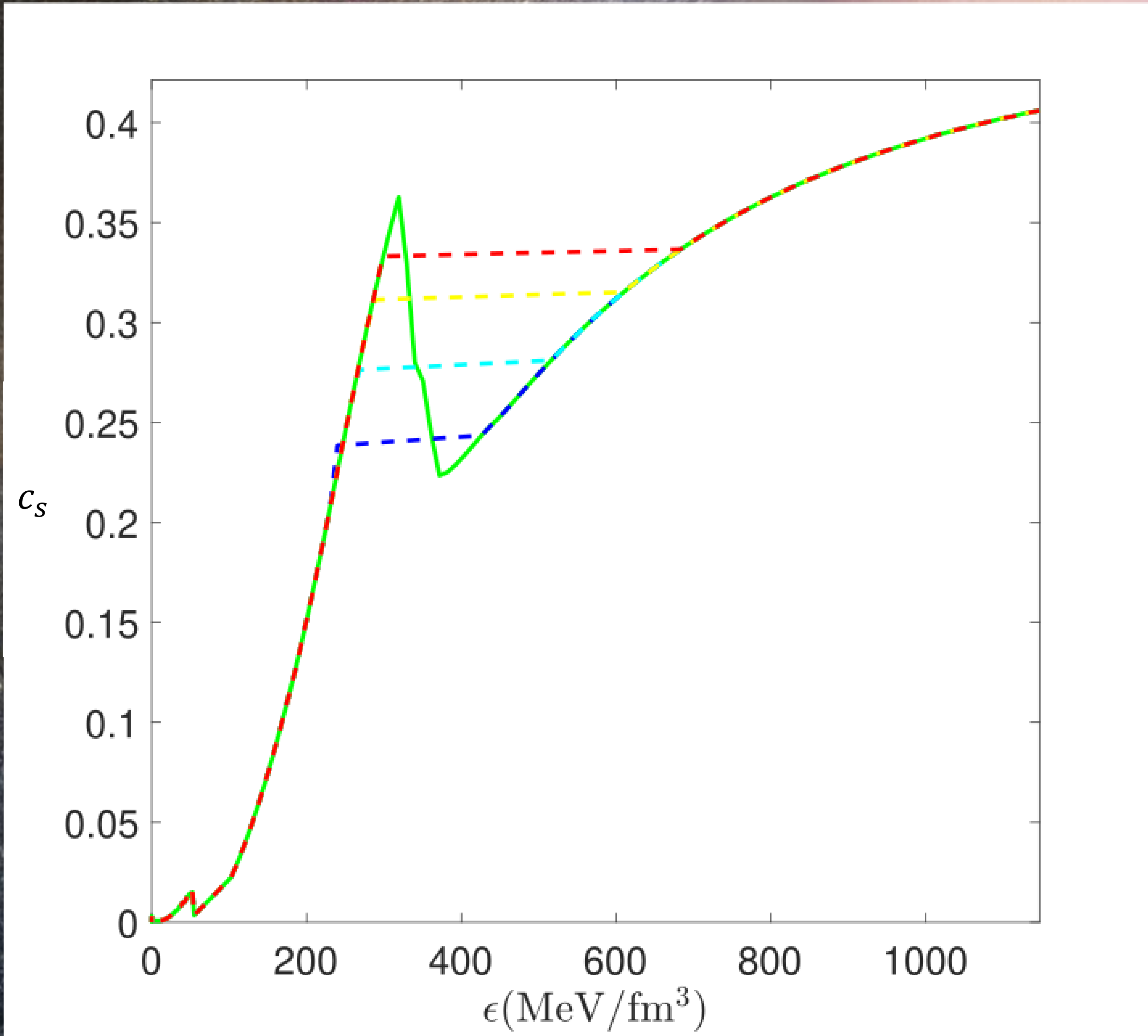
- Let's consider neutron energy levels in a cold dense nuclear matter
- The condition for the Λ hyperon to appear is:

$$\mu_n > m_\Lambda$$

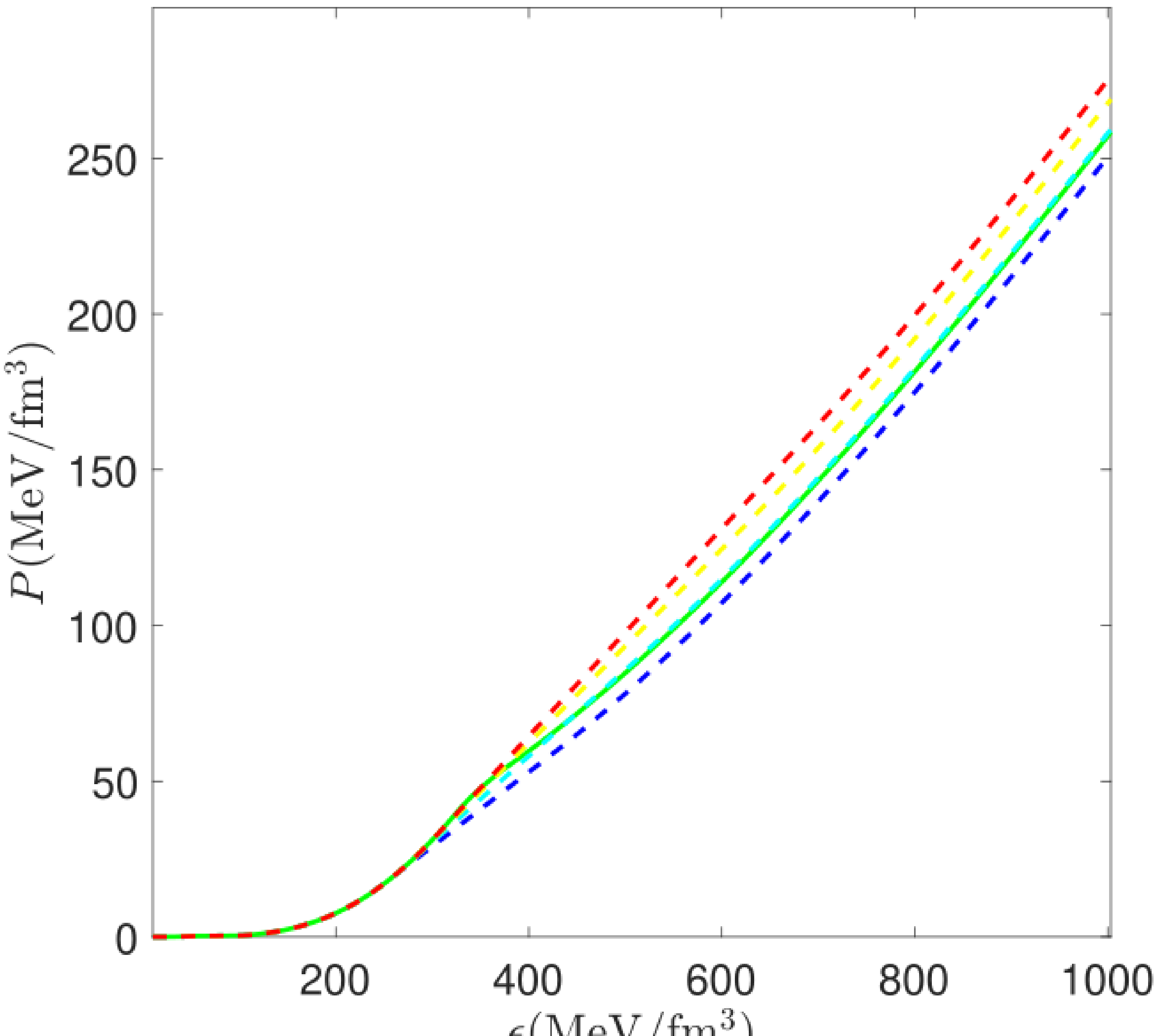
- In analogous way other hyperons can be created too
- The equilibrium condition is determined by the chemical potentials of the species and charge neutrality:



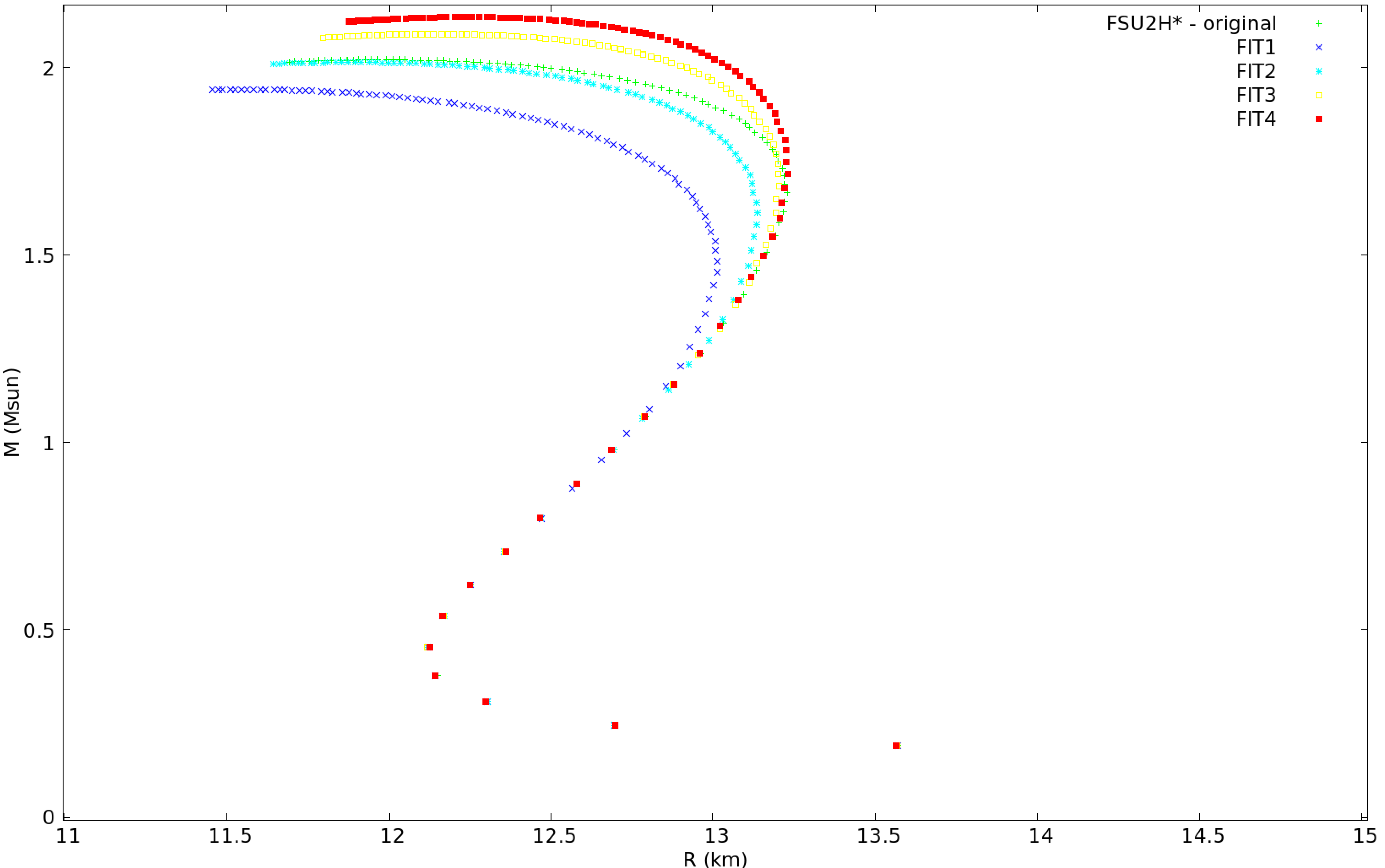
$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_n$$
$$\mu_{\Sigma^+} = \mu_p$$
$$\mu_{\Sigma^-} = \mu_{\Xi^-} = 2\mu_n - \mu_p$$



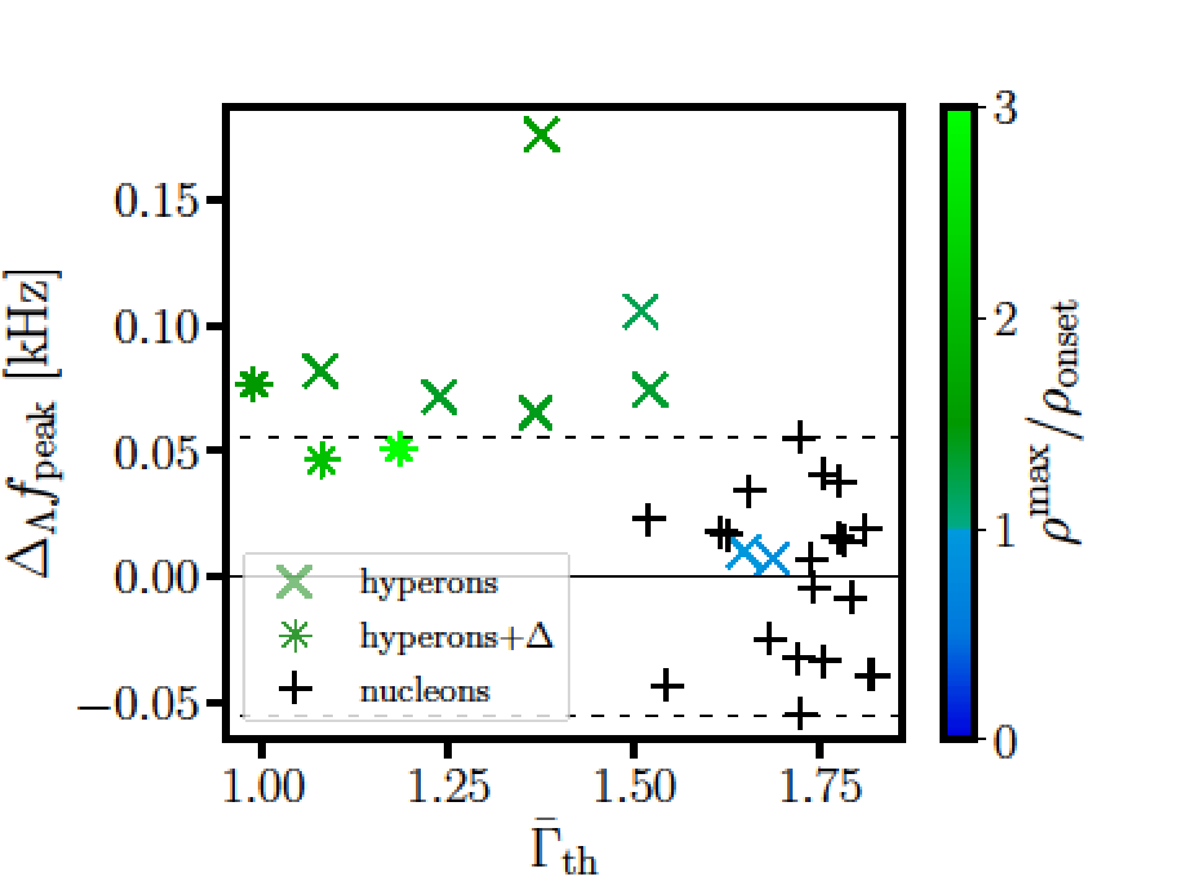
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
c_s
0
200
400
600
800
1000
$\epsilon(\mathrm{MeV/fm^3})$



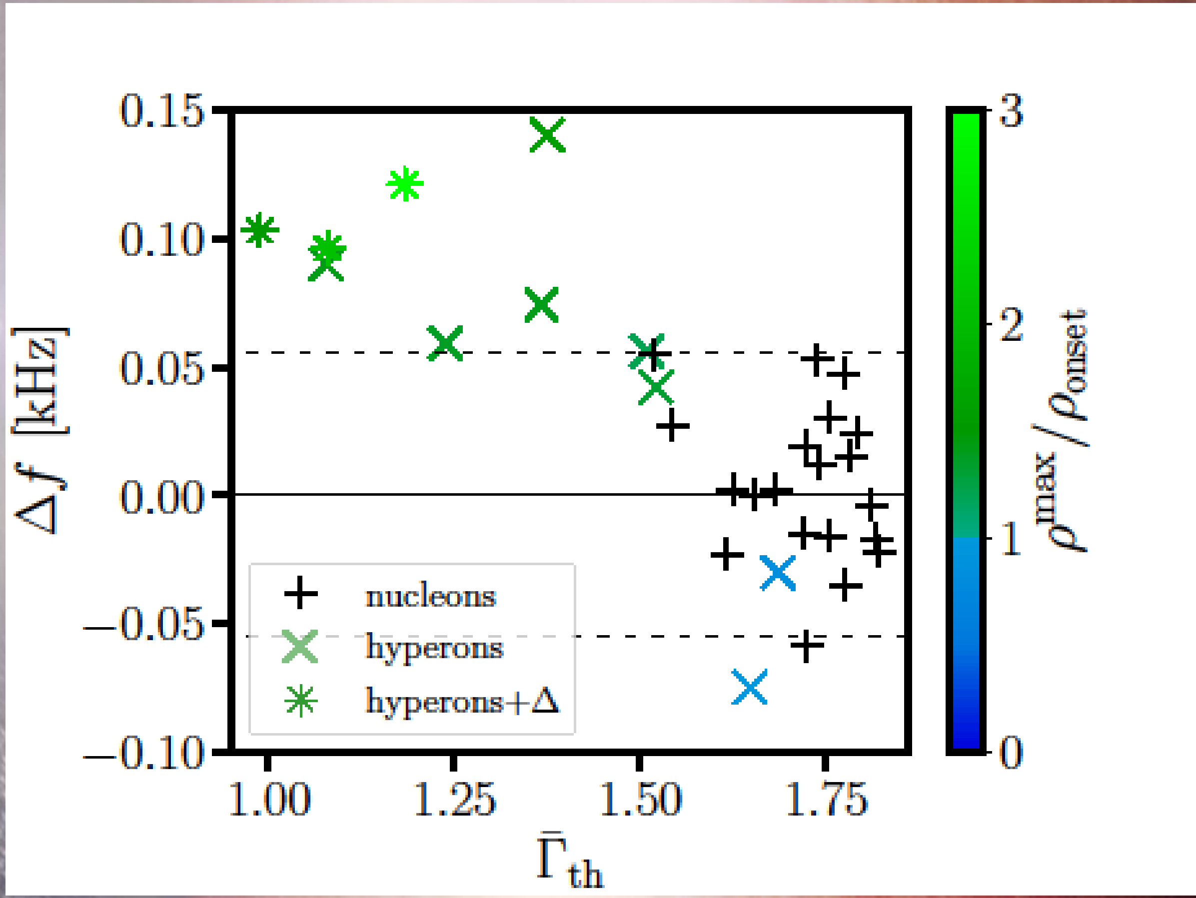
$P(\mathrm{MeV/fm^3})$
0
50
100
150
200
250
200
400
600
800
1000
$\epsilon(\mathrm{MeV/fm^3})$



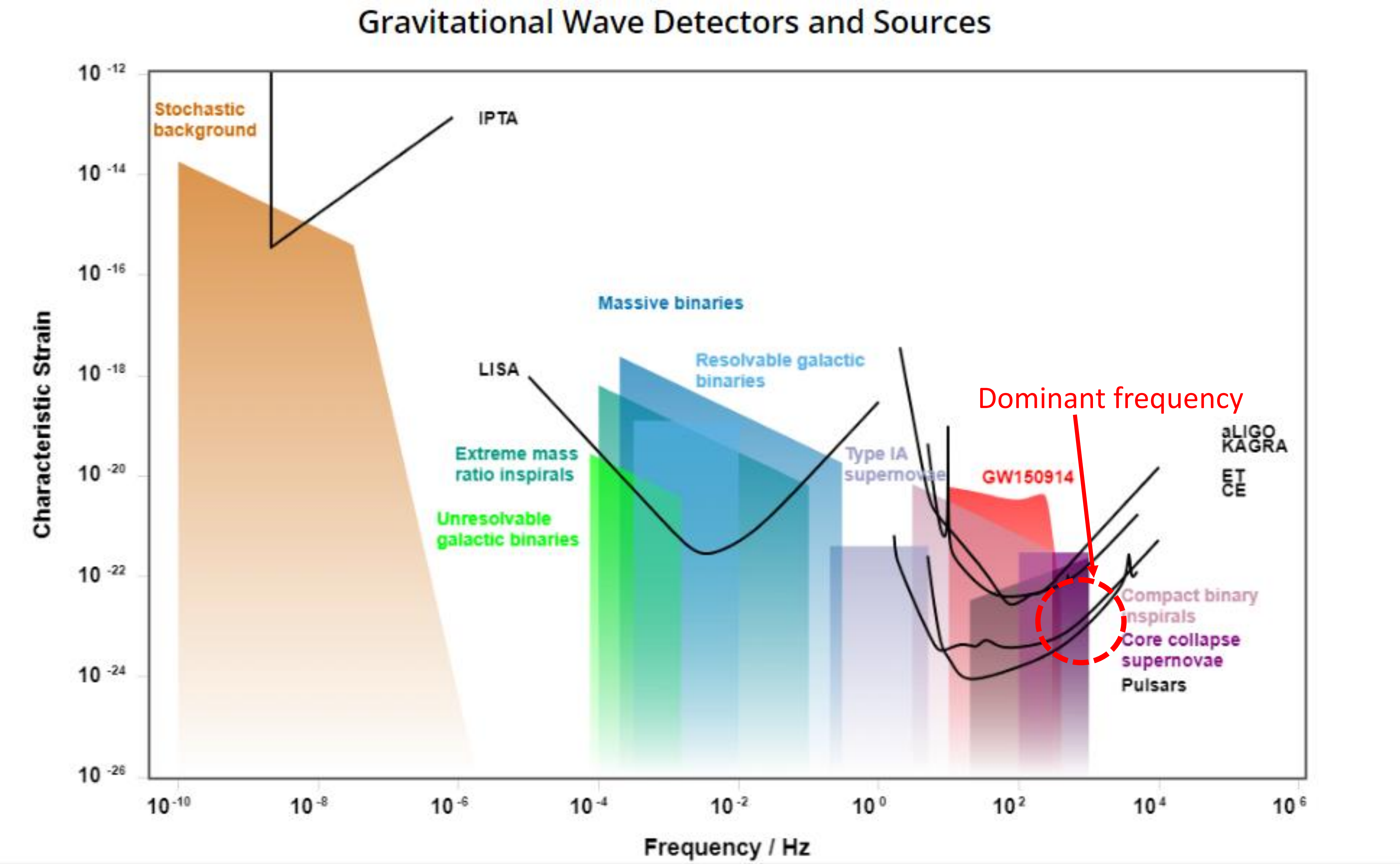
FSU2H* - original
FIT1
FIT2
FIT3
FIT4
M (Msun)
R (km)
0
0.5
1
1.5
2
11
11.5
12
12.5
13
13.5
14
14.5
15

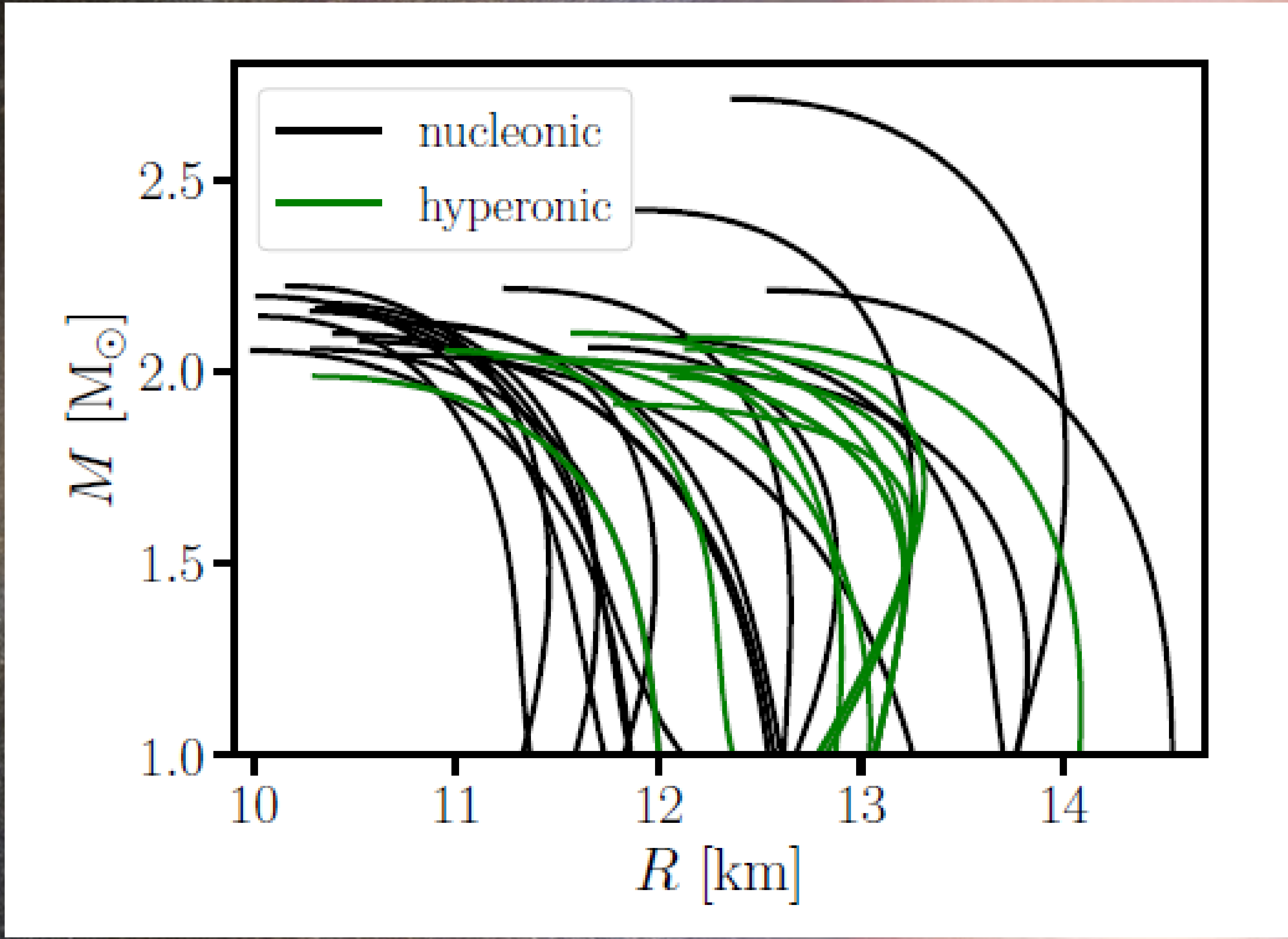


$\Delta_\Lambda f_{\rm peak}$ [kHz]
$\bar{\Gamma}_{\rm th}$
$\rho^{\rm max}/\rho_{\rm onset}$
hyperons
hyperons+Δ
nucleons



Δf [kHz]
$\bar{\Gamma}_{\rm th}$
$\rho^{\rm max}/\rho_{\rm onset}$
nucleons
hyperons
hyperons+Δ


Gravitational Wave Detectors and Sources
Characteristic Strain
Frequency / Hz
Stochastic background
IPTA
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Type IA supernovae
GW150914
Dominant frequency
aLIGO
KAGRA
ET
CE
Compact binary inspirals
Core collapse supernovae
Pulsars



Mass-Radius curves obtained using the EoSs considered in this work